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Collection Efficiencies of Various Airborne Spray Flux Samplers Used in Aerial Application Research*

ABSTRACT: A low air speed, spray dispersion tunnel was constructed and used to evaluate the collection efficiency of passive spray flux collectors. The dispersion tunnel utilizes an air-assisted nozzle to generate a spray cloud with a $D_{V0.5}$ of 18.5 ($\pm$0.4) μm at air speeds ranging from 0.4–4.0 m/s. A sampling protocol was developed to minimize spray flux and air speed variation effects while providing a check on theoretical collection efficiency calculations. A soda straw and monofilament line was placed on either side of a nylon screen cylinder collector, and all three were positioned in the center of the tunnel's cross-sectional area. Twelve replicated trials were conducted at air speeds of 0.4, 1.3, 2, and 3.8 m/s. Droplet size was measured every replication using a Sympatec HELOS laser diffraction system. Using theoretical collection efficiencies for cylinders and the measured fractional droplet size, the actual flux was estimated from the volume of spray collected on the soda straw and monofilament samplers and used to determine the collection efficiency of the nylon screen cylinder. Collection efficiency increased with air speed for all collectors and results ranged from 5 to 40 % for the soda straws, 46 to 83 % for the monofilament line, and 9 to 98 % for the nylon screen cylinders. Collection efficiency data are crucial to the evaluation of field collected data from aerial application research studies with respect to mass accountability and comparisons to other studies and drift model results.

KEYWORDS: collection efficiency, spray sampling, flux measurements, spray collection, drift

Introduction

Movement of sprays within and off of target areas is a critical concern for applicators, neighboring landowners, and researchers. Ideally, all of the material applied should be deposited within the targeted swath on the targeted pest or crop. Realistically, a portion of the spray remains airborne and is carried downwind for some distance. Airborne spray leaving the targeted area reduces the applied dosage, and could cause hazards or other detrimental environmental impacts. With greater environmental awareness and increased visibility of agricultural application practices, there is an increased desire to account for the entirety of applied materials.

The measurement and quantification of the airborne spray is difficult. Researchers have used passive collection media such as cotton string or cord [1–5], nylon string [6,7], various flat tapes [2–4], soda straws [8], horizontal tubes or cylinders [9,10], and wire [11] to measure spray flux, which is the amount of spray that passes through an area. Additionally, several active samplers have been reported including rotating impactors [5,12,13] and isokinetic samplers [14]. Collection efficiency (CE) is defined as the fraction of spray droplets approaching a surface or collector that actually deposits on that surface. Due to the unique shape and physical characteristics of the different samplers/collectors, each has a unique CE which is dependent on droplet size and wind speed. The active samplers are further complicated when the sampling rate differs from the aspiration rate [5]. Without knowing the CE of the collectors used in a study, it is difficult to interpret and compare with other studies that used different collectors, or perform mass balance analysis on collected data. Comparing the collected data to modeled data (such as by AGDISP) is also difficult without a thorough understanding of the collection efficiency of the sampler used in the study.

The theoretical CEs of droplets on cylindrical, spherical, long ribbon, and disc shaped collectors were carefully measured and reported by May and Clifford [15]. Their research examined the impaction of 20,

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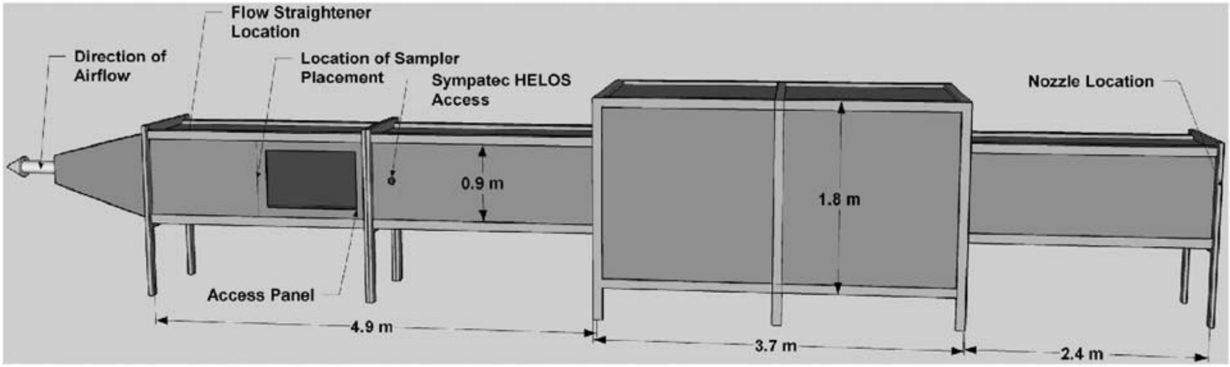

FIG. 1—*Spray dispersion tunnel layout and key locations.*

30, and 40-μm droplets of dibutyl phthalate (density of 1 g/cm^3) on spheres (2.7, 1.3, 1.1, 0.5, and 0.2-cm diameters), disks (2.9, 1.4, 1.0, 0.5, and 0.2-cm diameters), cylinders (2.0, 1.4, 1.0, 0.5, and 0.2 cm diameters), and ribbons (2.0, 1.3, 0.8, 0.1, and 0.1-cm widths) under air speeds of 2.2, 3.1, 4.5, and 6.2 m/s. They found that their measured efficiencies for cylindrical collectors agreed with theoretical calculations of Langmuir and Blodgett [16], as reported in May and Clifford [15]. An equation fit to the May and Clifford [15] data for cylinders is presented and used in this research. Not all collectors fit these ideal shapes and thus require experimental determination. Researchers have used a number of methodologies for collection efficiency evaluations including testing and exposure under ambient field conditions [14,17] to small scale wind tunnels [5,15,18] and mathematical and computer modeling [12,13,19]. Salyani et al. [17] found that under field conditions, cylindrical samplers (2-mm diameter polyester string) collected 2.3 times more spray than ribbon collectors (25.4-mm wide cotton ribbon). Cooper et al. [5] found CEs of 40 % to over 100 % at wind speeds of 0.3 to 3 m/s, respectively, for yarn samplers. One of the more unique sampling media, and flat vertically oriented nylon screen, was tested by Fox et al. [18]. They found that these screens captured 50–70 % of the spray, depending on droplet size and air speed.

One difficulty using these screens for a spray drift study was that changes in wind direction changed the sampler's frontal area as a consequence of the orientation geometry. With varying winds, determination of an area for flux calculations was difficult. Rolling and securing the screens into a cylindrical shape made the frontal area independent of wind direction, but the change in sampler geometry also changed the collection efficiency. As these screens do not fit shapes whose collection efficiency can be theoretically calculated, the collection efficiency needed to be determined experimentally. The objective of this research was to experimentally evaluate the collection efficiency of nylon screen cylinders as passive airborne spray flux samplers.

Methods

Dispersion Tunnel

A low air speed, spray dispersion tunnel with a mixing chamber was constructed for use in airborne spray sampler passive collector CE studies (Fig. 1). The tunnel cross-sectional area was designed and constructed to a 0.9 by 0.9 m (3 ft by 3 ft) square area. The overall tunnel consists of a 2.4-m (8-ft) long entry section at the beginning of which a spray nozzle is mounted. The entry section enters into a 1.8 by 1.8 by 3.7 m (6 by 6 by 12 ft) mixing chamber. A 4.9-m (16-ft) long section (two 2.4 m (8 ft) sections), also 0.9 by 0.9 m square, exits the mixing chamber. A flow straightener consisting of a 5 by 5 cm grid section 0.75 m in length was placed in the 0.9 by 0.9 by 2.4 m section where it exits to the fan. A fan pulls air throughout the system (Fig. 1) with an effective air speed in the tunnel ranging from 0.4 to 6.7 m/s (or 1 to 15 mph).

The test portion of the tunnel was the center of the last 2.4 m (8 ft) section before the fan. An access panel was created to allow for placement and recovery of collectors. Additionally, two holes were cut (centered vertically on the walls), on each opposing wall, 1.8 m (6 ft) upstream of the test portion to allow for placement of a Sympatec HELOS laser diffraction droplet sizing system, shown in Fig. 2 (Sympatec Inc., Clausthal, Germany).

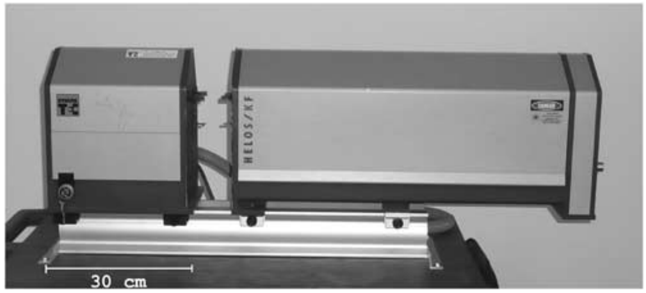

FIG. 2—*Sympatec HELOS laser diffraction droplet sizing system. Show here mounted on a single rail for visibility. The two sections are mounted on either side of the dispersion tunnel such that the laser and detector lens are aligned.*

Spray was released into the tunnel using an air assisted nozzle (Advanced Special Technologies, Winnebago, MN). The nozzle was designed to be used on the Terminator ULV Sprayer (Advanced Special Technologies, Winnebago, MN). The dual venturi style, stainless steel nozzle produces a $D_{V0.5}$ of 20.4 μm and 21.7 μm for water-based and oil sprays, respectively [20]. For this work, the spray nozzle was removed from the Terminator sprayer and connected to a compressor with a pressure regulator. The self-feed tube from the nozzle was attached to an inline flow meter. This allowed for a metered material release to the spray nozzle. The nozzle was operated at 689 kPa (100 psi) and fed 10 mL of Orchex 796 mineral oil (Calumet Lubricants Co., L.P., Indianapolis, IN) with Uvitex fluorescent dye at the rate of 0.2 g/L of oil. Air velocity measurements were made in the center of the sampling section during all replications using a hot-wire anemometer (Extech Instruments, Model 407119A, Waltham, MA).

Droplet Sizing

A Sympatec HELOS laser diffraction droplet sizing system (Sympatec Inc., Clausthal, Germany) was used to measure droplet size data. The HELOS system uses a 623 nm He-Ne laser and was fitted with an R5 lens, which resulted in a dynamic size range of 0.5 μm to 875 μm in 32 sizing bins. Tests were performed within the guidelines provided by ASTM Standard E1260: Standard Test Method for Determining Liquid Drop Size Characteristics in a Spray Using Optical Nonimaging Light-Scattering Instruments [21]. Droplet sizing data measured included volume median diameter ($D_{V0.5}$), the 10 and 90 % diameters ($D_{V0.1}$ and $D_{V0.9}$) [22]. $D_{V0.5}$ is the droplet diameter (μm) where 50 % of the spray volume or mass is contained in droplet of lesser diameter. $D_{V0.1}$ and $D_{V0.9}$ values describe the proportion of the spray volume (10 and 90 %, respectively) contained in droplets of the specified size or less.

Data Collection and Processing

Trials consisted of twelve replications at targeted air velocities of 0.4, 1.3, 2.0, and 3.8 m/s. Each replication consisted of three samplers, soda straw, monofilament line, and nylon screen cylinders (16 fibers/cm a porosity of 56 %; Filter Fabrics Inc, Goshen, IN, Part number 1420) collocated in the center 0.3 by 0.3 m (Fig. 3) section of the tunnel downstream of the HELOS Sympatec laser diffraction access location. Based on previous work [23] the three samplers in the center section were arranged with the monofilament line and the soda straw on each outer edge and the nylons screen cylinder in the center. The monofilament line and soda straw alternated locations (Fig. 3) each replication. The actual flux across the nylon screen cylinder was calculated as the average of the two outside actual fluxes (the measured fluxes corrected by the calculated theoretical CEs). Differing collectors were chosen for the outside locations, as opposed to two soda straws or two monofilament lines, in an effort to provide a check on the calculated CE data. Both samplers are cylindrical collectors, which have different collection efficiencies and considering that and their size will collect different amounts of material, assuming that Langmuir and Blodget [16] and the calculation of collection efficiency is correct, the actual flux per unit area should be the same. Previous evaluations of this approach found that over ten replications, that the experimental CE was within 5 % or less of the theoretical CE at air speeds from 0.4 up to 4.0 m/s [23].

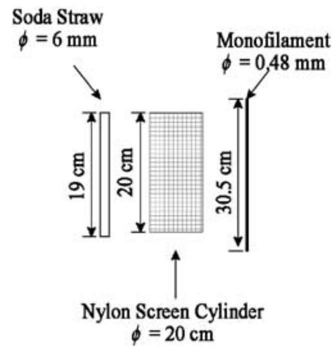

FIG. 3—*Monofilament line, nylon screen cylinder, and soda straw arrangement in the test section of the dispersion tunnel.*

Collection Efficiency and Flux Calculations of Center Sampling Study Data

For each replication conducted, a series of calculations were made in order to return the CE for the nylon screen cylinder. In summary, the steps taken were (1) obtain the measured flux from the three samplers; (2) correct each sampler for the percent of tracer recovered; (3) using the measured droplet size distribution, calculate the theoretical CE for the soda straw and monofilament collectors; (4) determine the actual flux across the soda straw and monofilament collectors by correcting the measured flux by the CE, therefore returning an expected concentration per unit area; (5) estimate the actual flux across the nylon screen cylinder as the average of the actual fluxes from Step 4; and (6) calculate the nylon screen cylinders CE using the flux measured by the screen and the estimated actual flux. The calculations made during these steps are discussed in greater detail in the sections below.

Step 1: Measured Fluxes—During each replication, droplet sizing information was collected using the HELOS Sympatec laser diffraction system and air speed information was collected with the hot-wire anemometer. After each replication, sample media were collected and placed into individually labeled plastic bags. Prior to placement of new sample media, test stands were cleaned with acetone. The bags were brought back to the laboratory for processing. After pipetting 20 (straws and monofilament) or 40 (nylon screen cylinders) mL of hexane into each bag, the bags were agitated, and 6 mL of the effluent was poured into a cuvette. The cuvettes were then placed into a spectrofluorophotometer (Shimadzu, Model RF5000U, Kyoto, Japan) with an excitation wavelength of 372 nm and an emission at 427 nm and a minimum detection level of 0.07 ng/cm^3.

The fluorometric readings were converted to $\mu L/cm^2$ based on readings from known sample concentrations and the projected area of the sampler. For this work, flux is defined as volume of spray that passed through a given unit two-dimensional vertical area over the whole of each test replication. As a result, flux has units of volume per area per time with time being equivalent to a replication. As such, flux numbers are reported in this manuscript in units of $\mu L/cm^2$ with time being implicit. Actual flux, F_{actual}, is defined as the actual total volume of spray passing through a given vertical unit area for the whole of a given replication.

For each sampler, the measured flux, $F_{sampler}$, is the calculated volume of spray deposited over the projected area of the sampler. The soda straw's projected area, A_{straw}, is the straw diameter (6 mm) by the length (19.1 cm), or 11.5 cm^2, the monofilament's projected area, A_{string}, is the string diameter (0.5 mm) by the length (30.5 cm), or 1.4 cm^2, and the nylon screen cylinder's projected area, A_{screen}, is the cylinder diameter (7.3 cm) by the length (20.3 cm), or 148 cm^2.

Step 2: Recovery Adjustment—The recovery adjustment was determined by spiking ten clean samplers of each type with a known volume of the spray material. Samples were bagged and washed following the same procedure described earlier, with both straws and monofilament being washed in 20 mL of hexane and nylon screen cylinders washing with 40 mL of hexane. Spectrofluorophotometric analysis returned a quantity of material based on the wash procedure which was then compared to the volume initially placed on the sampler. The soda straws showed an average recovery of 91 % (SD=6.2 %), monofilament line

samples showed an average recovery of 87 % (SD=5.8 %), and the nylon screen cylinders had a recovery rate of 79 % (SD=1.1 %). These values were used to correct the measured fluxes.

Step 3: Calculation of Theoretical Collection Efficiency—To calculate the theoretical collection efficiency for the soda straw and monofilament collectors, the following steps were taken for each droplet size bins measured by the laser diffraction system. Droplet size distribution, as measured by the laser diffraction system, ranged from 4.5 μm to 875 μm in 31 bins. First, the $\mathrm{Re}_{\mathrm{drop}}$ was calculated for each size bin using Eq 1. The droplet Reynolds number, Re_{drop}, is a dimensionless number that characterizes fluid flow around a particle [24].

$$\mathrm{Re}_{drop} = \frac{\rho_g V_o d}{\mu} \tag{1}$$

where:

Re_{drop} = Droplet Reynolds number (unitless)
ρ_g = Moist air density, ρ_{ma} (calculated), kg/m^3

$$\rho_{ma} = \frac{P_b - \Phi P_s}{0.054(t_{db})} + \frac{\Phi P_s}{0.086(t_{db})} \tag{2}$$

P_b = Barometric pressure, kPa
P_s = Saturated steam pressure at t_{db}, kPa
Φ = Relative Humidity/100 (unitless)
t_{db} = Temperature dry bulb (measured), °R
V_o = Air speed, m/s
d = Bin droplet diameter, μm
μ = Air viscosity, kg/(m*s)

$$\mu = \mu_o \left(\frac{a}{b}\right)\left(\frac{T}{T_o}\right)^{3/2} \text{ Sutherland's Formula [25]} \tag{3}$$

μ_o = Reference viscosity at T_o, 0.01827 cp
a = $0.555T_o + 120$
b = $0.555T + 120$
T_o = Reference T, 524.07 °R
T = Measured T in degrees °R

Next, the stop distance was calculated via the Mercer [26] method (Eq 4). The stop distance represents the distance a particle will travel in still air if all external forces acting on it were removed [24].

$$S = \frac{\rho_d d}{\rho_g}\left[\mathrm{Re}_{drop}^{1/3} - \sqrt{6}\arctan\left(\frac{\mathrm{Re}_{drop}^{1/3}}{\sqrt{6}}\right)\right] \tag{4}$$

ρ_d = droplet density, 850 kg/m^3
S = Stop distance, m

Now the Stokes number, St, can be calculated using Eq 5. The Stokes number characterizes a particles resistance to change in direction with fluid streamlines around an obstacle with higher Stokes number meaning an increased resistance to direction change by a particle [23]. This ratio of stop distance to collector size was used by May and Clifford [15] to express the collection efficiency of different types and sizes of objects placed in the path of an aerosol or particulate spray.

$$\mathrm{St} = \frac{S}{\lambda} \tag{5}$$

St = Stokes number, unitless
λ = Diameter of sampling cylinder, m

From this the collection efficiency of the cylinder for the given droplet size bin is calculated using Eq 6.

TABLE 1—*Droplet size data averaged over all twelve replications for each air speed tested.*

Air speed (m/s)	D_{V10}[a] (μm)	D_{V50}[a] (μm)	D_{V90}[a] (μm)
0.4	10.7 (0.2) c	18.1 (0.3) c	33.4 (0.9) c
1.3	11.6 (0.1) a	20.4 (0.5) a	42.8 (1.1) b
2	11.7 (0.1) a	20.4 (0.3) a	43.7 (0.9) a
3.8	11.2 (0.1) b	19.3 (0.3) b	43.6 (1.0) a

[a]D_{VI}, is the diameter such that i % of the total volume of droplets is in droplets of smaller diameter. Data are presented as Mean (Standard Deviation) where $n=12$. Means within each column followed by the same letter are not significantly different (Means separation determined using Fisher's LSD at $\alpha=0.05$ level).

$$E_{\text{i sampler}} = \frac{\text{St}^{A}}{(\text{St}+0.38)^{B}} \tag{6}$$

$E_{\text{i sampler}}$ is the fractional collection efficiency for the ith size droplet bin for the sampler. A and B are adjustable parameters. For a typical sigmoid curve, $A=B=2$. To fit the May and Clifford [15] data for the collection efficiency of a cylinder versus Stokes number, these parameters are modified slightly, with $A=1.995$ and $B=2.028$. This fits the data very well up to a Stokes number of about 25, with the collection efficiency being constant after that. The upper end (Stokes number >15) and lower end (Stokes number <0.15) are extrapolations. Stokes number ranged from 0.004 to 1.7 (4.5 to 105 μm, respectively) at 0.4 m/s up to 0.03 to 10.1 (4.5 to 105 μm, respectively) at 3.8 m/s. The overall sampler collection efficiency (over all droplet size bins), CE_{sampler}, for a given replication is the sum over all size bins of fractional collection efficiencies, $E_{\text{i sampler}}$, multiplied by the volume fractions of spray as measured by laser diffraction, X_i laser.

Step 4: Actual Flux Across Soda Straw and Monofilament Collectors—The actual flux, F_{actual}, across the soda straw and monofilament collectors was calculated using the sampler measured flux, as determined and corrected in Steps 1 and 2, and the spray droplet distribution as measured by the laser diffraction system. To determine F_{actual} (for the soda straw and monofilament measured fluxes), F_{sampler} is adjusted using the theoretical collection efficiency as calculated from May and Clifford [15]. From this, F_{actual} is calculated as F_{sampler} over CE_{sampler} (Eq 7).

$$F_{\text{actual}} = \frac{F_{\text{sampler}}}{CE_{\text{sampler}}} \tag{7}$$

Step 5: Estimate of Actual Flux Across Nylon Screen Cylinder—Given that the goal is to determine the collection efficiency of the nylon screen cylinders as a theoretical CE cannot be calculated, the actual flux, F_{actual}, across the screens was estimated as the average of the actual fluxes determine for the soda straw and monofilament collectors.

Step 6: Nylon Screen Cylinder Collection Efficiency—Using the estimated actual flux, F_{actual}, determine in Step 5 and the nylon screen cylinder corrected measured flux, F_{sampler}, determined in Steps 1 and 2, the nylon screen cylinders CE is calculated using Eq 8.

$$CE_{\text{screen}} = \frac{F_{\text{actual}}}{F_{\text{screen}}} \tag{8}$$

Results and Discussion

Droplet Size

There was little variation in droplet size within replications conducted for each air speed. Although there was some statistical separation in drop size among the $D_{V0.1}$, $D_{V0.5}$, and the $D_{V0.9}$ values (Table 1), the numerical differences were very small except for the $D_{V0.9}$ measurement at 0.4 m/s air speed. At the

TABLE 2—*Means and standard deviation of collection efficiencies for each sampler and air speed combination. N = 12.*

	Soda Straw	Sampler Monofilament	Nylon Screen Cylinder
0.4 m/s			
Mean	4.7	46.0	9.1
Standard Deviation	0.56	2.2	1.4
Range	3.6–5.5	41.1–47.9	7.1–11.6
1.25 m/s			
Mean	22.5	72.9	32.1
Standard Deviation	1.8	2.2	6.1
Range	21.2–27.8	67.3–77.2	22.7–46.0
2 m/s			
Mean	28.7	77.9	63.7
Standard Deviation	1.1	0.4	12.8
Range	26.6–30.0	77.0–78.4	44.2–84.8
3.8 m/s			
Mean	40.3	82.6	97.7
Standard Deviation	1.1	0.2	26
Range	38.8–42.2	82.4–83.0	66.7–123

lowest air speed, the larger droplets likely settled out before reaching the test section of the tunnels. These differences did not affect the collection efficiency results because the methodology used factored in the droplet size data for each replication.

Collection Efficiency

As the air speed increased from 0.4 to 3.8 m/s, the collection efficiency (CE) increased for each of the samplers (Table 2). The mean CE for the soda straw increased from 4.7 to 40.3 % when the air speed increased from 0.4 to 3.8 m/s. The mean CE for the monofilament line increased from 46.0 to 82.6 % when the air speed increased from 0.4 to 3.8 m/s. The mean CE for the nylon screen cylinder increased from 9.1 to 97.7 % when the air speed increased from 0.4 to 3.8 m/s. The CE values for the soda straw and the monofilament line had very low standard deviations, while the nylon cylinder CE values were more variable. The higher variability in the screen CE values, as compared to the soda straw and monofilament CE values, is likely a result of the interpolation procedure used to calculated the screen's CE. The soda straw and monofilament CE values are theoretically calculated based on air speed and droplet size data, which at a given air speed changed little from replication to replication, resulting in very similar CE values. The screen CEs are calculated based on actual flux values which are calculated based on the soda straw and monofilament measured data, which had a greater degree of variation than the droplet size and air speed data. In theory, the screen CE values should be very similar from replication to replication.

The variation in CE values calculated for the nylon screen cylinders is greater at higher air speeds. At

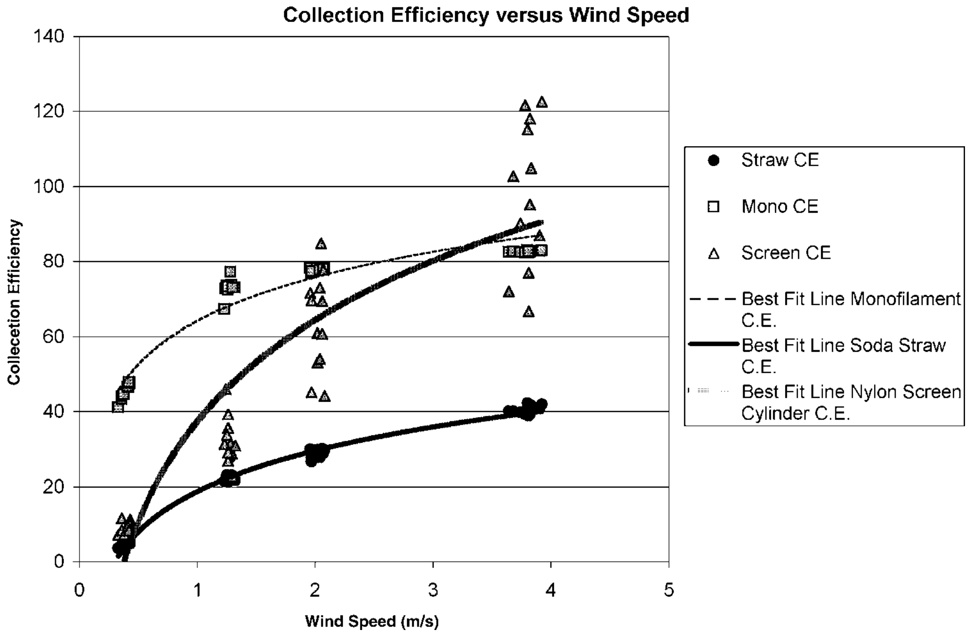

FIG. 4—*Collection efficiency of soda straw, monofilament line, and nylon screen cylinder collectors versus wind speed.*

the higher air speeds, the sprayed material had less residence time in the tunnel resulting in decreased mixing. Generally, the monofilament line was the most efficient collection device, while the soda straw was the least efficient at the air speeds and for the droplet spectrum used in this study. The monofilament was a better collector for the droplet sizes used in this study as the ratio of droplet stop distance to collector diameter, and thus CE, was larger for the monofilament. If sampling for droplets that have larger diameters than the diameter of the monofilament, the soda straw sampler would be a better choice as these larger droplets would not be completely collected by the monofilament due to their larger size. There were CE values over 100 % for the nylon screen cylinders at the 3.8 m/s air speeds which was likely a result of droplets passing through the front face of the screen cylinder and depositing onto the inside screen face.

For each of the collectors, best fit lines were calculated (Fig. 4). The equation for each of best fit lines are shown in Eqs. 9–11, where y=collection efficiency and x=air speed from 0.4–3.8 m/s.

Best fit line for the soda straw data:

$$y = 15.6\ \mathrm{Ln}(x) + 18.7\ \ R^2 = 0.99 \tag{9}$$

Best fit line for the monofilament string data:

$$y = 16.8\ \mathrm{Ln}(x) + 64.1\ \ R^2 = 0.93 \tag{10}$$

Best fit line for the nylon screen cylinder data:

$$y = 38.9\ \mathrm{Ln}(x) + 37.4\ \ R^2 = 0.82 \tag{11}$$

At lower air speeds the nylon screen cylinder's CE is greater than, but very close to that of the soda straws, but at higher air speeds, the screen's CE is greater than, but very close to that of the monofilament. Based on previous work with air flow through screen material [27] the author's hypothesis is that at the lower air speeds, there is very little air penetration through the screens; therefore, the screen acts as a solid cylinder. At higher air speeds, there is greater air penetration, allowing the droplets that do not impact the first layer of screen to have a chance to deposit on the second layer of screen (i.e., the backside of the screen cylinder) and with the air penetration, collection efficiencies are more associated to the diameter of individual fibers than the diameter of the whole sampler, as seen at the lower airspeeds.

Conclusions

This work examined the collection efficiency of nylon screen cylinder collectors used by the authors as passive collectors during aerial application spray drift studies. The screen's collection efficiency was

determined by comparison with two other collectors, monofilament line and a soda straw, with known collection efficiency. The nylon screen cylinder's collection efficiency ranged from 9 % at 0.4 m/s air speeds to near 100 % at air speeds of 3.8 m/s. The methodology presented in this paper can be applied to any sampler used to measure airborne spray droplets and highlights the importance of air speed on the collection efficiency of a sampler. This work supports ongoing aerial application spray accountability studies allowing field measured data to be compared across multiple studies and with modeled data.

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